Measurement of Location Deviations of Flat Surfaces

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***Abstract* — In many cases, the installation and operation of high-tech equipment often requires centering and adjustment of objects or parts with flat surfaces and respectively to control their mutual location. This paper presents the measurement of the mutual arrangement of flat surfaces placed nominally in one plane by means of a dual-channel laser measuring system.**

Key words: measurement, mutual arrangement, centering, adjustment, laser measurement system

I. INTRODUCTION

In the process of installation and operation of high-tech equipment, is often necessary to control mutual location when centering and adjusting objects or parts with flat surfaces. For example, in linear and circular accelerators is necessary to control the centering and angular orientation of the flanges (Fig. 1) of the separate sections of the waveguide system. The requirements are to be parallel to their axes and their centers to lie on one line, i.e. the flat surfaces must lied in the same plane

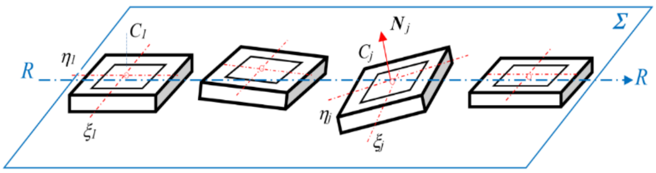

Fig.1 Scheme of objects with requirements for centering and angular orientation of the axes ξ, η and the normal N_j of the separate flat surfaces

In many cases, multi-channel measuring systems are used to solve such metrological problems. The object of this report is the application developed dual-channel laser measuring system [2] for measuring the centering and angular orientation of planar surfaces.

II. PRINCIPLE SCHEME OF THE LASER MEASURING SYSTEM

The schematic diagram of the laser system is shown in Fig. 2. The system contains the following main modules: laser diode emitting unit 1, beamsplitter 2, wedge compensator 3, reflective prism 4, polarizing compensators 5 and 6, measuring retro-reflectors 7, PSD 8, and polarizing filter 9.

The beam emitted by the laser unit 1 is divided by the beamsplitter 2 (prism-cube) into two orthogonally polarized beams, one of which is oriented parallel to the other beam by means of the reflective prism 4. The parallelism of the two measuring channels (I and II) is adjusted with the wedge compensator 3. The beams are reflected by the retroreflectors 7 (triple prisms) and after reflection by the prism-cube 2 (beam I) and prism 4 (beam II) respectively to the photodetector module with PSD 8. In the beams the polarization compensators 6 (plates λ/4) are introduced for rotation of the plane of polarization.

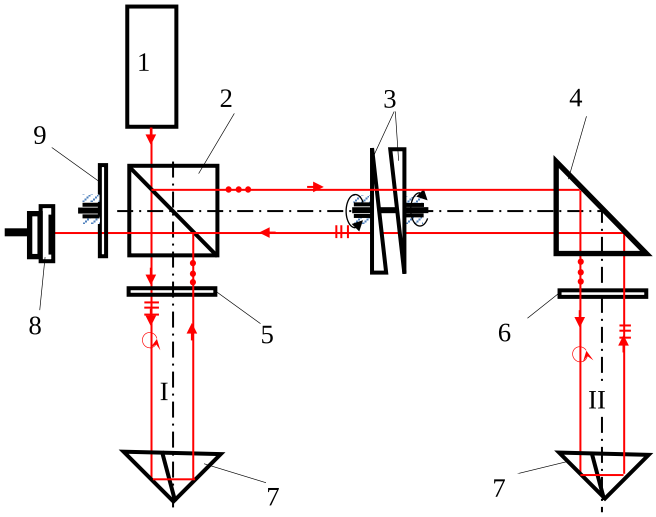

Fig. 1 Dual-channel laser system for control of mutual arrangement of surfaces

The switching between the two measuring channels is performed by means of the polarizing filter 9.

III. MEASUREMENT OF DEVIATIONS ON THE LOCATION OF FLAT SURFACES

Към обектите представени на Fig.1 са предписани изисквания за пространственото им разположение спрямо базова равнина Σ, отнасящо се до координатите на центъра C_j и ъгловата ориентация на осите ξ_j и η_j както следва:

To the objects presented in Fig. 1 are prescribed requirements for their spatial arrangement with respect to the reference plane Σ, relating to the coordinates of the center Cj and the angular orientation of the axes ξj and ηj as follows:

– the objects must be centered, i.e. the centers Cj on their flat surfaces lies on one line - the base line R;

– the axes of symmetry ηj and, respectively, ηj of the separate surfaces to be parallel to each other

– the axis ξj to be perpendicular and the axis ηj to be parallel to the common axis R ($\xi_j \perp R$ η_j // R);

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– the surfaces to lie in the base plane Σ, ie. their radius vectors to be perpendicular to it (Nj ⊥ Σ);

– j=1…q, where q is the number of controlled surfaces.

The reference plane *Σ* may be the plane common to all or a number of surfaces or the plane associated with one of the surfaces.

The basic line R according to which the location of the centers is assessed can be:

– the line associated with the extracted line of the centers (for example, the middle line or the line joining the centers of the two end surfaces);

– axis η_0 of one of the surfaces accepted as base.

The tasks for the control of objects with similar configuration can be successfully solved using a dual-channel laser measurement system (LMS) based on the energy axis of a laser beam.

The scheme of the arrangement of the surfaces and the measured points is presented in Fig. 3.

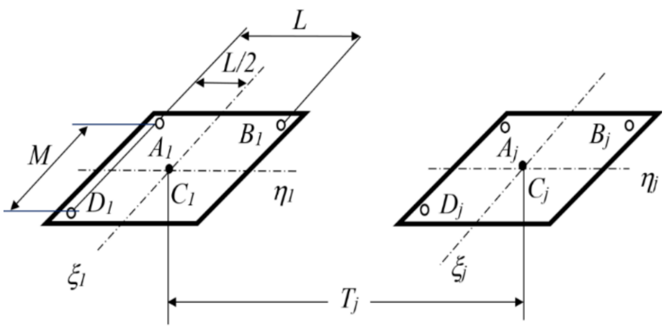

Fig. 2 Schematic diagram of the location of the surfaces and the measured points

The coordinates of three points on each surface (A_j, B_j and D_j), identical to the centers C_j and the axes of symmetry - the coordinate axes ξ_j and η_j of the surfaces should be measured. The three points lie on two mutually perpendicular lines ($A_jB_j \perp A_jD_j$), and the point C_j is the mean for the hypotenuse A_jD_j.

The centers C_j of the measured surfaces lie nominally on a straight line and at a distance T_j from the center of the first surface C_1.

The measurement scheme with the dual-channel laser system is presented in Fig. 4.

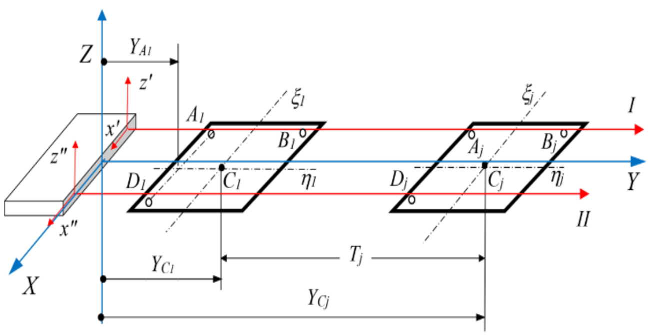

Fig. 3 Measurement scheme with the two-channel laser system

The two parallel laser beams are oriented nominally parallel and symmetrically to the line of the centers of the surfaces.

The points A_j and D_j are located symmetrically with respect to the axis η_j and at a distance M from each other, according with the distance between the channels of LMS, and the points B_j and A_j are symmetrical with respect to the axis ξ_j and at a distance L/2 from it.

The coordinates of the points A_j (x'_{Aj}, z'_{Aj}) and B_j (x'_{Bj}, z'_{Bj}) in the coordinate system x'y'z 'with axis y', defined by the axis of beam I and the coordinates of point D_j (x'_{Dj}, z'_{Dj}) in the system x"y"z" with axis y", defined by beam II axis.

The results of the primary measurement information for the coordinates of the points are brought to the coordinate system XYZ, the axis OY of which is set by the median of oy' and oy", and the directions of the axes OX and OZ - from the axes of the used two-coordinate PSD:

$$\left| \begin{aligned} X_{A_j} &= x_{A_j} - \frac{M}{2} \\ Y_{A_j} &= y_{A_j} = Y_{C_j} - \frac{L}{2} \\ Z_{A_j} &= z_{A_j} \end{aligned} \right. \qquad (1)$$

$$\left| \begin{aligned} X_{B_j} &= x_{B_j} - \frac{M}{2} \\ Y_{B_j} &= Y_{A_j} + L = Y_{C_j} + \frac{L}{2} \\ Z_{B_j} &= z_{B_j} \end{aligned} \right. \qquad (2)$$

$$\left| \begin{aligned} X_{D_j} &= x_{D_j} + \frac{M}{2} \\ Y_{D_j} &= Y_{A_j} = Y_{C_j} - \frac{L}{2} \\ Z_{D_j} &= z_{D_j} \end{aligned} \right. \qquad (3)$$

The coordinates of the center C_j, which is the midpoint of the hypotenuse B_j-D_j of the right triangle $A_jB_jD_j$ (Fig. 3) can be determined by the formulas:

$$\left| \begin{aligned} X_{C_j} &= \frac{X_{B_j} + X_{D_j}}{2} \\ Y_{C_j} &= \frac{Y_{B_j} + Y_{D_j}}{2} = Y_{C_1} + T_J \\ Z_{C_j} &= \frac{Z_{B_j} + Z_{D_j}}{2} \end{aligned} \right. \qquad (4)$$

IV. Evaluation of the Accuracy of Centering of Surfaces

The centering accuracy is estimated by the displacement of the center C_j of the surface from the reference axis $\overline{R-R}$ in the two coordinate planes XOY and ZOY.

The displacement is defined as the deviation from the straightness relative to the line associated with the extracted line of the centers (middle line; line joining the centers of the two end surfaces).

The mean line, as is well known, is constructed by the "least squares method".

When using the line joining the centers of the end surfaces (C_1 and C_q) the projections of the base line in the coordinate planes XOY and ZOY are described by the equations:

$$\left| \begin{aligned} (R_1 - R_q)_x &\Rightarrow X = X_{C_1} + \left(X_{C_q} - X_{C_1}\right) . \frac{T_j}{T_q} \\ (R_1 - R_q)_z &\Rightarrow Z = Z_{C_1} + \left(Z_{C_q} - Z_{C_1}\right) . \frac{T_j}{T_q} \end{aligned} \right. \tag{5}$$

The displacement is defined as the distance from the projection of the point C_j to the projection of the base line in the corresponding coordinate plane.

Since the angular displacement of the base line $\overline{R-R}$ relative to the coordinate axis OY is relatively small, the formulas can be used to determine the displacements ΔX_j, ΔZ_j (decentralization) in the first approximation:

$$\left| \begin{aligned} \Delta X_j &= X_{C_j} - \left(X_{C_1} + \frac{X_{C_q} - X_{C_1}}{T_q} T_j \right) \cong EFL_{jX} \\ \Delta Z_j &= Z_{C_j} - \left(Z_{C_1} + \frac{Z_{C_q} - Z_{C_1}}{T_q} T_j \right) \cong EFL_{jZ} \end{aligned} \right. \tag{6}$$

Angular displacements are considered as rotations α_X, α_Y and α_Z on the surface about the OX axis, about the OY axis and about the OZ axis, respectively, and are determined using the results of measuring the coordinates of the points A_j, B_j и and D_j by formulas:

$$\left| \begin{aligned} \alpha_{X_j} &= \frac{Z_{B_j} - Z_{A_j}}{L} \\ \alpha_{Y_j} &= \frac{Z_{D_j} - Z_{A_j}}{M} \\ \alpha_{Z_j} &= \frac{X_{B_j} - X_{A_j}}{L} \end{aligned} \right. \tag{7}$$

where α_X, α_Y и α_Z are in radians.

If it is necessary to determine the deviations from flatness EFF of the total surface of the individual elements, the measured points A_j, B_j and D_j are considered as points from the extracted total surface Σ_0.

Based on the results of the measurement and alignment of the coordinates of the points to the XYZ coordinate system, the associated on the extracted total surface Σ_0 base plane Σ (usually the middle plane) is constructed, according to which the deviation from flatness EFF is determined by the respective algorithms.

V. Analysis of Methodological Errors

The main methodological errors are as result of the influence of the algorithm used to estimate the deviations of the form and location of the surfaces of the controlled object.

A Errors in determining the displacement of the centers of the surfaces ΔX and ΔZ

According to the proposed algorithm, the displacements ΔX_j, ΔZ_j of the center C_j (X_{Cj}, Y_{Cj}, Z_{Cj}) are determined by the distance from the center to the base line, measured in the direction of the respective coordinate axis (Fig. 5), and not as a distance from the center to the base.

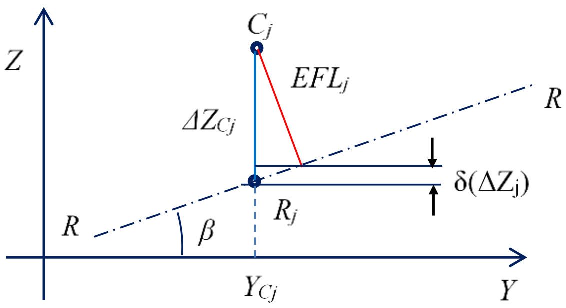

Fig. 4 Error of determining center offset

At angular displacement β of the base line relative to the OY axis of the coordinate system, this leads to a relative error in determining the displacement:

$$\delta(\Delta X_j) = \Delta X_{j.} \sin^2\beta \tag{8}$$

As. when measuring the OY axis of the system is oriented nominally parallel to the line of the centers, the angle β is relatively small and the error is negligibly small. For example, at a slope of β = 1°, the relative error is below 0.04%.

B Errors in determining the angular displacements α_X, α_Y and α_Z.

The rotation of the surface around the OX axis is estimated by the difference $\Delta Z_{AB} = Z_B - Z_A$ in the coordinates of points A and B.

The analysis shows that the rotation of the surface about the axis OZ at an angle α_Z does not affect the result for the angle of rotation α_X, while the rotation of the surface about the axis OY at an angle α_Y leads to an error $\delta\alpha_X$ in estimating the angle of rotation α_X about the axis OX:

$$\delta\alpha_X = \frac{\delta(\Delta Z)_{AB}}{L} = \alpha_X \alpha_Y^2 \tag{9}$$

The rotation of the surface about the axis OZ does not affect the result of the angle of rotation α_Y about the axis OY. However, rotating α_X on the surface about the OX axis introduces an error $\delta\alpha_Y$ in estimating α_Y:

$$\delta\alpha_Y = \frac{\delta(\Delta Z)_{AD}}{L} = \alpha_Y \alpha_X^2 \tag{10}$$

The rotation of the surface about the OX axis does not affect the result of the angle of rotation α_Z about the OZ axis, while the rotation α_Y of the surface about the OY axis introduces an error $\delta\alpha_Z$ in estimating α_Y:

$$\delta\alpha_Z = \frac{\delta(\Delta X)_{AB}}{L} = \alpha_Z \alpha_Y^2 \tag{11}$$

Since the angles of rotation α about the individual axes are relatively small, the influence of the rotation about a given axis on the result of the evaluation of the angular position of the surface relative to the other two axes is negligible. For example, when rotating the surface at an angle α_Y = 2°, the relative error in determining α_X and α_Z is less than 0.1%.

Conclusion

A method for assessing the mutual arrangement during alignment and adjustment, as well as during control in the process of operation of objects or details with flat surfaces nominally lying in one plane has been developed.

The proposed algorithms allow determining the position of the surfaces by measuring the coordinates of points on them with the developed dual-channel laser measuring system.

The analysis of the methodological errors due to the influence of the angular displacements shows that the proposed algorithm provides an adequate assessment of the spatial arrangement of the surfaces.

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References

[1] Diakov D. I., H. N. Nikolova, V. A. Vassilev, Large-Scaled Details Flatness Measurement Method, DOI: 10.1109/FarEastCon.2018.8602859, Electronic ISBN: 978-1-5386-9535-7; Print on Demand (PoD) ISBN: 978-1-5386-9536-4, Far East Con-2018 — INTERNATIONAL MULTI-CONFERENCE ON INDUSTRIAL ENGINEERING AND MODERN TECHNOLOGIES, October 2-4, Vladivostok, Russia 2018, Paper №2.331.

[2] Dichev, D., I. Zhelezarov, N. Madzharov,. System for Measuring the Attitude of Moving Objects, Using a Kalman Filter and MEMS Sensors. COMPTES RENDUS DE L ACADEMIE BULGARE DES SCIENCES, volume 72, issue 11, 2019, pp. 1527-1536, ISSN 2367–5535.

[3] Dichev, D., Koev, H., Bakalova, T., Louda, P. An Algorithm for Improving the Accuracy of Systems Measuring Parameters of Moving Objects. *Metrology and Measurement Systems*. Volume 23, Issue 4, 2016, pp. 555-565, ISSN 0860-8229, https://doi.org/10.1515/mms-2016-0041

[4] Kalimanova I., D. Dyakov, H. Nikolova, R. Miteva, Izmereniye geometrii volnovodnykh komponentov portativnoy koordinatno-izmeritelnoy mashinoy, Metrologiya ta priladi, Naukovo-virobnichiy zhurnal 1 II 2014, s. 86-90, ISSN 2307-2180.

[5] Miteva R., Izsledvane na modeli za aproksimatsiya na materialen etalon s izpolzvaneto na virtualno-mehanichen etalon za pravolineynost, Sbornik dokladi ot Mezhdunarodna nauchna konferentsiya „Uniteh 2019“, Gabrovo, 15-16.11.2019, tom 2, s. 330-334, ISSN 1313-230X.

[6] Nikolova H. N., D. I. Diakov, V. A. Vassilev, Form Deviations Measurement of Planar Surfaces by Overlapping Measuring Positions Using Reference Plane Method, XXVIII International Scientific Symposium "Metrology and Metrology Assurance 2018" September 10-14th, 2018, Sozopol, Bulgaria, pp.65-69, ISSN 1313-9126.

[7] Dichev, D., Koev, H., Bakalova, T., Louda, P. A Model of the Dynamic Error as a Measurement Result of Instruments Defining the Parameters of Moving Objects. *Measurement Science Review*, Volume 14, Issue 4, 2014, 183-189, ISSN 1335-8871, https://doi.org/10.2478/msr-2014-0025

[8] Radovanovic M., G. Brabie, I. Zhelezarov, Investigation on surface roughness of carbon steel machined by abrasive water jet, 35th International conference on production engineering, Kraljevo, Kopalnik, Serbia, 2013, p.133-136, ISBN 978-86-82631-69-9.

[9] Slavov, St.; Kirov K.; „Modelirane na harakteristikite na regulyarni relefi s izpolzvane na metodite za barzo prototipirane, Izvestiya na Sayuza na uchenite, gr. Varna, Seriya „Tehnicheski nauki“ № 1; 2016 god. str 76-84, ISSN 1310-5833.

[10] Todorov, T.S., Mitrev, R.P., Tudjarov, B.N., Nikolov, R.F.; Qualitative analysis of oscillating magnetomechanical system (2019) IOP Conference Series: Materials Science and Engineering, 618 (1), art. no. 012054, https://www.scopus.com/inward/record.uri?eid=2-s2.0-85076113277&doi=10.1088%2f1757-899X%2f618%2f1%2f012054&partnerID=40&md5=7829b3eb372c2b4bcc37279851692721, DOI: 10.1088/1757-899X/618/1/012054

[11] Todorov, T., Nikolov, N., Nikolov, R., Sofronov, Y., Kochev, L., Optimization of micro-electro-mechanical piezoelectric energy harvesters with interdigitated electrodes, (2019) Journal of the Balkan Tribological Association, 25 (3), pp. 535-545, https://www.scopus.com/inward/record.uri?eid=2-s2.0-85081207578&partnerID=40&md5=e4419478ba2ec9d0683bf15fed897984

[12] Malakov, I., Topalova, I., System development of representative criteria for choosing an optimal variant of technical product (2009) Annals of DAAAM and Proceedings of the International DAAAM Symposium, pp. 1335-1336. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84904336234&partnerID=40&md5=067a9d35912eeca806e7344421aceb8d, ISSN17269679, ISBN 978-390150970-4

[13] Dyakov D., I. Kalimanova, Lazerni sistemi za izmervane geometrichni parametri na ploski povŭrkhnini na golyamogabaritni obekti i sŭorŭzheniya, Sofiya, 2019, Softtreĭd, ISBN 978-954-334-217-4

[14] Nikolova H. Izmervane na otkloneniyata na formata i razpolozhenieto na ravninni povŭrkhnini na golyamogabaritni obekti po metoda na opornata ravnina, 2019 g., Softtreĭd, ISBN 978-954-334-214-3

[15] Vassilev V., Nikolova H., Programno osiguryavane na sistemi za izmervane na otkloneniyata na formata i razpolozhenieto na povŭrkhninite i osite na detaĭlite, Sofiya, Softtreĭd, 2020, ISBN 978-954-334-231-0